A DETERMINATION OF THE TENSION AT THE SURFACE OF EGGS OF THE ANNELID, *CHÆTOPTERUS*

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By means of the microscope-centrifuge, recently described by Harvey and Loomis (1930), it is possible to observe, and to photograph, using highest dry objectives, living cells while subjected to centrifugal forces thousands of times gravity.[1] The cells are mounted on a special slide fixed over the objective, which rotates on the centrifuge at a distance of 11 cm. from the axis of rotation. By total reflecting prisms the image is brought to the axis of the centrifuge and then vertically upward where it is observed with a stationary ocular. The light, a condenser discharge in mercury vapor, is arranged for stroboscopic illumination, flashing on with each revolution of the centrifuge. The image is perfectly clear and steady at 4000 R.P.M.

Chætopterus eggs, as is well known from the work of F. R. Lillie (1909), pull apart into fragments under the influence of high centrifugal forces. The centrifuge-microscope allows us to observe clearly the series of changes in this process and to make exact measurements from which it is possible to calculate the tension at the surface of the egg. This process is illustrated for unfertilized *Chætopterus* eggs by the photographs of Fig. 1.

The first three rows show ten stages in the formation of a fragment or spherule containing oil, taken through the microscope-centrifuge while revolving about 4000 R.P.M., 5 seconds' exposure. It will be noted that No. 5 is a double exposure (by mistake) and shows the exact change in position which takes place in 1 minute. At one stage the protoplasm is drawn out into long filaments with the oil spherule at one end. In the pulling off of this oil spherule the appearance is that of a drop of molten glass slowly falling from a heated rod. When the oil finally breaks away, it moves slowly (as long as it can be observed in

[1] The microscope-centrifuge was devised in collaboration with Mr. Alfred L. Loomis and constructed in his private laboratory at Tuxedo Park, New York. The author expresses his deep appreciation to Mr. Loomis for the hospitality of the laboratory. It is contemplated that the instrument will be placed on the market by the Bausch and Lomb Company. For description see Harvey and Loomis in *Science*, 1930, **72**: 42.

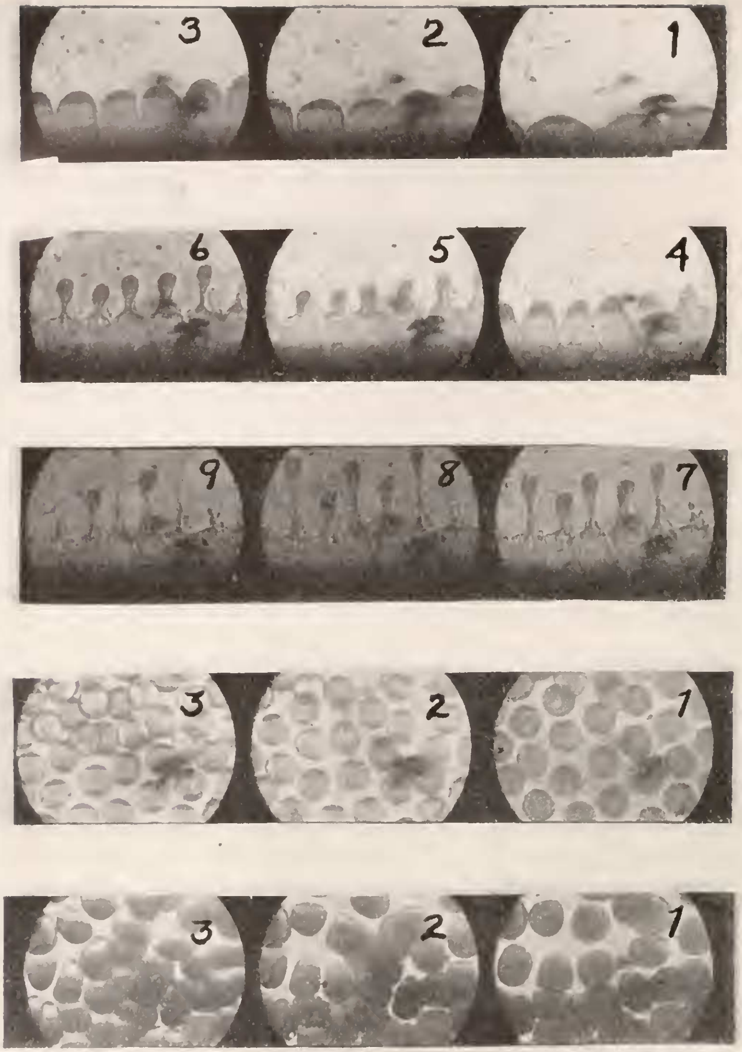

FIG. 1. Photographs of unfertilized eggs taken with a Leica camera through the microscope-centrifuge (radius 11 cm.), showing successive changes (examine from right to left) in stratification of granules and in shape of eggs. Magnification, 87 diameters. The direction of the centrifugal force is downward.

First three rows, *Chætopterus* exposed for 5 seconds at 35, 55, 95, 165, 205 and 265 (double exposure), 345, 375, 450, and 480 seconds after starting centrifuge. Speed of the microscope-centrifuge was 55 R.P.S. in the first row and 66 R.P.S. in the second and third rows. At the highest speed about 330 flashes of light occurred during the exposure.

Fourth row, *Cumingia* exposed 10 seconds at 35, 95 and 155 seconds after starting centrifuge. Speed 38 to 55 R.P.S. The eggs are separated by jelly.

Fifth row, *Arbacia* exposed 10 seconds at 45, 150, and 285 seconds after starting centrifuge. Speed 35 R.P.S. The eggs are partially separated by jelly.

the field of the microscope) to the surface of the sea water. Sometimes a clear fragment containing no yolk or oil globules will separate. These clear fragments are denser than sea water and sink; in fact, a clear fragment, one half containing oil globules, is heavier than sea water.

The pulling away of an egg spherule containing oil occupies about seven minutes at 1916 times gravity, and it will be noted that when an oil spherule breaks away the stalk does not round up immediately but remains for some time and only slowly rounds off. The stalk does not behave as if it were elastic like rubber, which would immediately recover when stretched, nor is it stiff, for one can observe these stalks waving back and forth in currents in the sea water during centrifuging. They appear like a very slow flowing plastic material such as tar.

The stalk is part of the original surface of the egg. Are we to regard that as having purely a surface tension at its boundary or a membrane of some sort with an elastic tension and a definite breaking strength, or should we think of the breaking strength of the stalk per cross sectional area? Perhaps the magnitude of this tension will allow us to decide. If we determine the buoyant force of the oil tending to draw apart the egg into fragments, we can equate this to a tension of the egg considered as acting only around the surface (surface tension or elastic tension of a membrane) or as acting over the whole cross sectional area of the stalk (internal friction of a plastic fluid), or a combination of the two.

Fortunately, it is easy to gain a rough idea of the buoyant force, which tends to pull apart the egg, by the following considerations. A maximum value for this force will be obtained if we consider oil rising through egg fluid rather than egg spherule rising through sea water. Let us assume the density of the oil is 0.915, the same as that of hen's egg yolk oil. By measuring the diameter of the oil spherule ($34\,\mu$) pulled away from the egg, we find that the volume of the oil is 75 per cent [2] of 2.05×10^{-8} cc. or 1.54×10^{-8} cc., and its mass is 1.41×10^{-8} grams. The density of the medium can be taken as 1.044, the average of Heilbrunn's (1926) values for *Arbacia* and *Cumingia* eggs, and slightly greater than sea water (1.0238) at Woods Hole at 20° C. Therefore, the buoyant force of the oil pulling inward toward the axis of the centrifuge will be $(1.044 - 0.915)/0.915 \times 1.41 \times 10^{-8} = 0.2 \times 10^{-8}$ grams $\times$ 980 $\times$ centrifugal force $(1916 \times g) = 3.75 \times 10^{-3}$ dynes. Since the yolk rests against the bottom of the slide, this will be the only force tending to pull the egg apart, and it will be counter-

[2] Since the oil granules are spheres and spheres packed in a volume occupy only 75 per cent of that volume.

acted by the surface tension or elastic tension (T) of the egg, acting around the circumference (πD) of the stalk of diameter (D) connecting oil spherule and egg at the moment the stalk breaks.[3] Hence $\pi DT = 3.75 \times 10^{-3}$ dynes.

The diameter of the stalk is found to be 9 μ by measurement. Solving, $T = 1.32$ dynes per cm. This is a maximum value, as it is likely the oil might have been pulled away with somewhat lower centrifugal forces, although it takes 7 minutes to pull apart at $1916 \times$ g. One dyne per cm. cannot be very far from the truth, perhaps 25 per cent error at most. If we are to regard this as a surface tension, it is very low, but might be compared to that of a water—isobutyl alcohol interface whose T is 1.76 dynes per cm. at 20° C. On the other hand, the value seems entirely too low for an elastic membrane tension.

If we regard the stalk of *Chætopterus* eggs as made up of homogeneous material, its breaking strength, S, would be $(\pi/4)D^2S = 3.75 \times 10^{-3}$ dynes or $S = 5900$ dynes per cm.^{2}, also an extremely small value. The breaking strength of rubber is about 100 million dynes per cm.^{2}

The long cylindrical stalk of centrifuged *Chætopterus* eggs would be a very unstable figure according to classical surface tension interpretation. Plateau showed that a cylinder breaks into drops when its length equals its circumference. This is a geometrical relation, independent of the value of the surface tension, provided the fluids have a low viscosity. In the derivation of surface tension formulas by the vibrating drop and vibrating jet methods the viscosity of the fluid is neglected for simplification. With very high viscosities the attainment of equilibrium conditions might take so long a time as to make thin cylinders stable figures for all practical purposes. With plastic fluids surface tension might be too small to overcome the internal friction.

The value of 1.3 dynes per cm. does not allow us to decide definitely whether the boundary of the egg exerts a surface tension or an elastic tension, but it does show that there can be no very firm "pellicle" around these eggs. The observed behavior of the stalk makes it quite certain that we are dealing with a very plastic material. If the tension were greater than fifty dynes per cm., a maximum value for liquid-water interfaces, we might say quite definitely that it was elastic membrane and not surface tension. Such may be the case in eggs like *Arbacia* and *Cumingia* which are not torn apart by much higher centrifugal forces, and show only a slight tendency to lengthen, as illustrated in rows 4 and 5 of Fig. 1.

[3] I am deeply indebted to Dr. Charles Zahn of the Physics Department, Princeton University, for suggestions regarding the interpretation of some of these surface tension phenomena.

Summary

A method is described, using the microscope-centrifuge, for calculating the tension at the surface of *Chætopterus* eggs, which gives an approximate *maximum* value of 1.3 dynes per cm.

LITERATURE

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